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# TRANSACTIONS

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OF

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*A paper presented at the 13th General Meeting of the American Institute of Electrical Engineers, New York, May 20th 1896. President Duncan in the Chair.*

# AN ANALYSIS OF TRANSFORMER CURVES.

BY CHAS. K. HUGUET.

One of the most noteworthy features of Prof. Ryan's famous paper on "Transformers,"[1] before this INSTITUTE, was the distortion of the primary current curve on open secondary. This distortion, Prof. Ryan ascribed to hysteresis, and this opinion seems to have been held by Fleming[2], Steinmetz[3], and every other writer since that time, with the single exception of Prof. Rowland.[4]

Dr. Sumpners had previously shown that, assuming hysteresis absent, a variation in the value of $\mu$ will superpose on the sinoidal magnetizing current a system of higher harmonics, causing it to become a symmetrically peaked curve. Prof. Rowland, however, went further, and declared that the presence of the distorting harmonics is due, not to hysteresis, but to change in permeability, the effect of hysteresis being capable of representation as a simple resistance. However, he simply expressed this theory mathematically, without giving any experimental verification, and it is doubtless for this reason that the results of his paper have not been accepted in their entirety. This apparent conflict of opinion seemed to warrant further investigation, and it was the object of experiments conducted by the writer at Tulane University in June, 1895, to throw light on this question by analyzing the current curve into its various components.

1. Ryan: "Transformers"; TRANSACTIONS, vol. vii. p. 1.
2. Fleming: "Alternate Current Transformer," vol. ii. p. 454.
3. Steinmetz: "On the Law of Hysteresis (Part III)"; TRANSACTIONS, vol. xi, pp. 781. 743.
4. Rowland: "Notes on the Theory of the Transformer"; *Philosophical Magazine*, vol. 34, p. 54. Also: *Electrical World*, July 9, 1892.
5. Sumpner: *Philosophical Magazine*, June, 1888, p. 468.

The low-tension coil of a 40-light Fort Wayne transformer was used as primary, and a run made at 100 volts and 140 ∼. The method employed in the measurement of the instantaneous values was essentially similar to the telephone method described by Nichols[1], a galvanometer being substituted for the telephone. A run was also made at 50 volts and 70 ∼, and the determination of the watts lost under these conditions, as well as under the preceding ones, enabled us to discriminate the eddy from the hysteresis losses in the usual manner[2]. In this case the total loss at 100 volts and 140 ∼ was 55 watts, of which 20.7 watts were due to eddies, and 34.3 watts to hysteresis. If we divide the

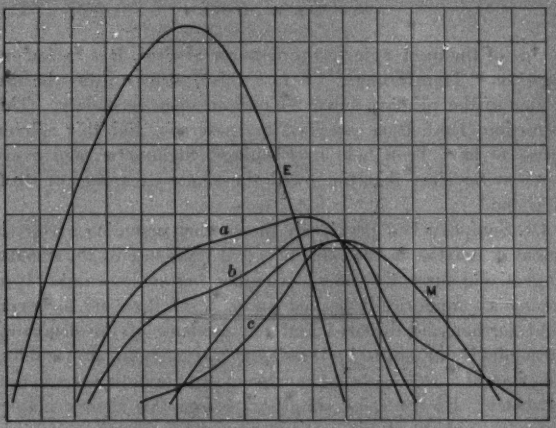


FIG. 1.—40-Light Transformer, 100 v 140 ∼.

watts lost by eddies by the E M. F. applied, we shall obtain the effective current due to eddies, and the ratio of this to the aforesaid E. M. F. is the conductance due to eddies.

If the instantaneous values of E. M. F. be multiplied by this conductance, and the resulting eddy current curve be substracted from the original current curve (*a*, Fig. 1), the remainder will be the hysteresis curve (*b*), *i. e.*, the curve that would be derived from the hysteresis loop. If in the same way we determine the conductance due to both eddies and hysteresis, *i. e.*, if we repre-

1. Nichols: "Laboratory Manual," vol. ii., p. 182.
2. Steinmetz: "On the Law of Hysteresis"; TRANSACTIONS, vol. ix., p. 50.

sent the hysteretic loss as one due to a simple constant resistance, and substract the effective current curve thus determined, from the original current $a$, the remainder $c$ will be a true wattless current, since the curve substracted itself accounts for the watts lost. In Fig. 1, this wattless remainder is very fairly symmetrical with respect to the flux curve M, and is of the peaked character to be expected with permeability variable and hysteresis absent. A similar treatment of Prof. Ryan's curve[1] yielded a wattless remainder ($c$, Fig. 2), of similar character. These results seemed to verify Prof. Rowland's theory, at least approximately.

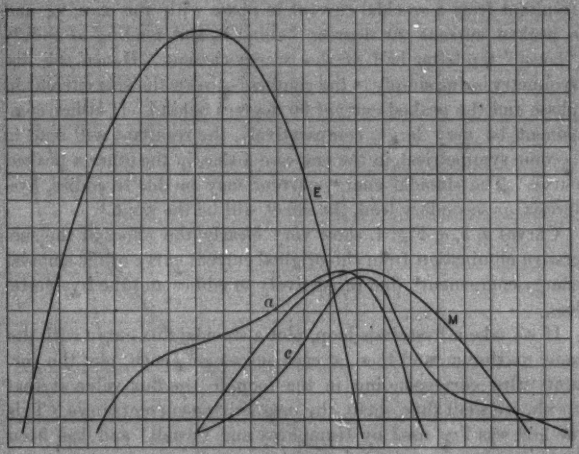


FIG. 2.

But equally strong proof is afforded by Figs. 7, 8, 9, 10 in Steinmetz "On the Law of Hysteresis (Part III.)",[2] for here the subtraction from the original wave, of its equivalent sine wave, leaves a wattless higher harmonic, in each case very nearly symmetrical with respect to the maximum magnetization. Hence these higher harmonics must be due almost entirely to variation in permeability, since hysteresis is essentially unsymmetrical with respect to the magnetization. It is worthy of note that in Fig.

1. Ryan: "Transformers"; TRANSACTIONS, vol. viii., p. 1.
2. TRANSACTIONS; vol. xi., pp. 718, 719.

10, in which the original current is most distorted, the wattless higher harmonic is most nearly symmetrical.

The state of the case seems to be, briefly, this: A variable value of $\mu$ will superpose upon the wattless sinoidal magnetizing current a symmetrical system of higher odd harmonics, which, since they are symmetrical with respect to the zero of E. M. F., will also be wattless, and the resultant magnetizing current will be a wattless peaked current. If now the transformer be heavily loaded, the sinoidal energy-current will completely hide the magnetizing current both in shape and phase. If, however, the energy-current be comparatively small, we will have a current resultant from a sinoidal current in phase with the E. M. F., and a peaked current 90 degrees behind it, and tending to unduly "boost" the latter half of the energy-current. Hence the dissymmetry is due simply to the conflict between the sine current in phase and the peaked current 90 degrees behind. If either component be very large, comparatively, the resultant will tend to become symmetrical, in the one case a sine, in the other a peaked curve. The sinoidal energy-current may be due to eddies, hysteresis, or secondary load, the effect will be the same.

Curves *a*, *b*, *c*, Fig. 1, show very clearly the effect of the successive elimination from the original current curve of the sinoidal energy-components, due respectively to eddies and the hysteretic loss.

If we take a hysteresis loop, plot a sinoidal flux curve with the same maximum, and then, at each successive epoch, plot the current value corresponding in the loop to the flux value at that epoch, we shall thus obtain the magnetizing current curve. This method was first used by Humphrey and Powell[1] and has been employed by numerous later writers.

If, however, at each epoch, we plot a current value, the mean of those given by the loop for rising and descending magnetization, we shall thus obtain the wattless magnetizing current. This curve is essentially symmetrical with respect to the flux curve, and consequently, as stated, wattless.

If this wattless magnetizing current be substracted from the original current, the remainder will be the hysteretic current curve, or, what is the same thing, we may plot at each epoch the half-width of the loop at the corresponding flux. A curve

1. Humphrey and Powell: "The Efficiency of Transformers"; TRANSACTIONS, vol. vii. Also *Electrical Engineer*, vol. x., 1890, p. 16.

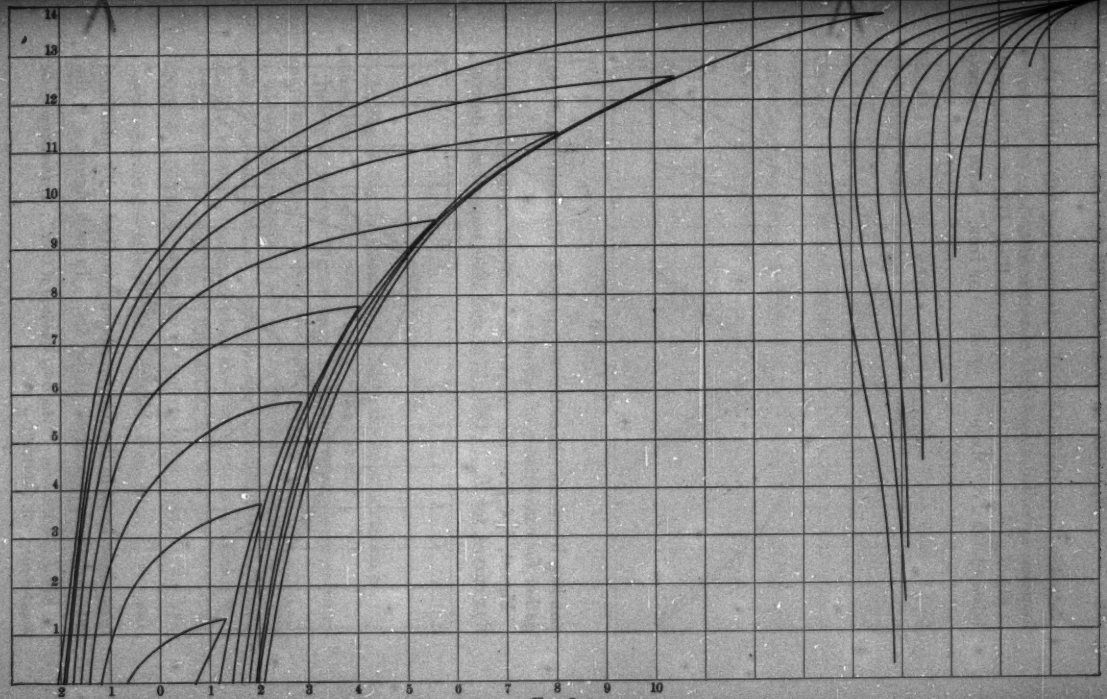


FIG. 3.

plotted between the flux and the corresponding half-width of the loop may be called a *hysteretic characteristic.*

Fig. 3 gives a set of half-loops from Ring III. in Ewing and Klaassen on the "Magnetic Qualities of Iron,"[1] with the corres-

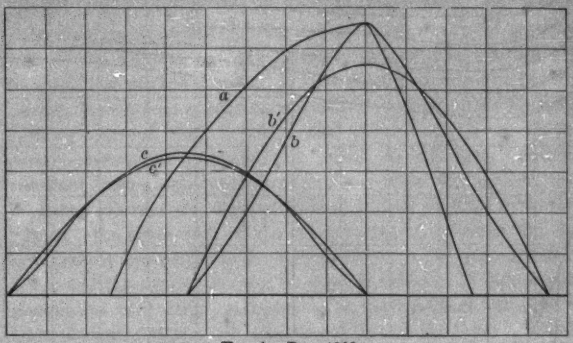


FIG. 4.—B = 1360.

ponding hysteretic characteristics, plotted with their maxima together for convenience of comparison.

Figs. 4, 5, 6 give the magnetizing current curves for sinoidal flux curves, for $B_{max.}$, 1360, 3720, and 5830, respectively, derived

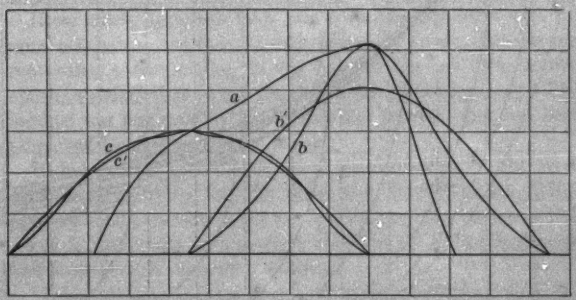


FIG. 5.—B = 3720.

from these loops in the manner above described, with additional curves derived by analysis of the first. In each figure, *a* is the

1. Ewing and Klaassen: "Magnetic Qualities of Iron"; *Transactions of the Royal Society*, vol. 184 (1893), p. 998.

original magnetizing current curve, $b$ the wattless magnetizing current, $b'$ its equivalent sine, which represents the flux curve in shape and phase, $c$ the hysteretic current, and $c'$ its equivalent sine.

The half-width of the loop is zero for maximum flux, and for any flux has the same value, but opposite sign for increasing and decreasing magnetization. Hence the hysteretic current has the same zeros as the E. M. F. curve, and is essentially symmetrical with respect to it, consequently essentially in phase, but it remains to determine the conditions under which it also has the sinoidal form.

In Fig. 5, for $B_{max.} = 3720$, $c$ lies very close to $c'$, having, indeed, the same maximum.

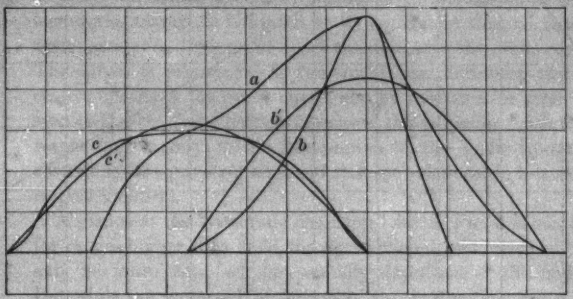


FIG. 6.—B = 5830.

In Fig. 4, for the lower range, 1360, the approximation is very close, but $c$ is slightly more *pointed* than the sine.

In Fig. 6, for the higher range 5830, the approximation is not quite so close, but $c$ is more *flattened* than the sine.

These approximations are quite close, but it is easy to determine the exact form of hysteretic characteristic necessary for a sinoidal hysteretic current, when the flux curve is sinoidal.

Let $E$ and $M$ (Fig. 7.) be sinoidal E. M. F. and flux curves, respectively, drawn to same size for convenience. Assume the hysteretic current due to a simple resistance, *i. e.*, $H = \frac{E}{R}$ (instantaneous values.) Then plot a curve between the flux value at each successive epoch and the hypothetical hysteretic current at that epoch.

M
E
5630
1380
E11

A hysteretic characteristic of the form thus determined will obviously satisfy the conditions.

This curve is the quadrant of an ellipse.

For $E^2 + M^2 = A^2$, where $A = E_{max.} = M_{max.}$ But $H = \frac{E}{R}$ by assumption, whence $H^2 R^2 + M^2 = A^2$, which is an ellipse, $H$ and $M$ being the variables.

For our purposes the quadrant tells the whole story, so that we may say that the assumption, for sinoidal E. M. F., of hysteresis as due to a simple resistance, is absolutely correct when the hysteretic characteristic is a quadrant of an ellipse.

If we compare this ideal curve with the hysteretic characteristics for the ranges used in Figs. 4, 5, 6, plotting each characteristic to a horizontal scale proportional to the virtual value of its hysteretic current, as indicated by its equivalent sine, we see the same manner and degree of approximation as in the cyclic curves. The ellipse is intersected by horizontal bars indicating the successive epochs in the cyclic curve, and by reference to these it is seen that each characteristic intersects the ellipse at a point corresponding exactly to the intersection of the cyclic hysteretic current by its equivalent sine, and that the relationship is in every respect identical.

A glance at the hysteretic characteristics in Fig. 3 shows that for ranges higher than 5830, the hysteretic current curve will not only be more flattened, but actually depressed in the middle. But while the increased distortion of the hysteretic current will introduce higher harmonics, yet the rapid diminution in the permeability on approaching saturation will introduce them much more rapidly with increase of the range, so that the distorting influence of the hysteretic current will be comparatively slight even at the higher ranges. At the highest ranges, as the one given by Steinmetz[1], mentioned above, $B = 16{,}000$ the inordinate peak of the wattless magnetizing current throws into oblivion higher harmonics from any other source.

To conclude: for sinoidal E. M. F.;

(1) Hysteresis may in all respects be replaced by a constant resistance if the hysteretic characteristic be the quadrant of an ellipse.

(2) This condition is approximately satisfied for moderate ranges of magnetization (such as are used in practice), in reason-

1. TRANSACTIONS, vol. xi., p. 719.

ably good iron, and the higher harmonics are negligible. There will usually be a particular range that will give a nearly perfect approximation. On contraction of the range, the hysteretic current becomes more pointed than the sine, and on expansion beyond the critical range, more flattened than the sine.

(3) The increased distortion of the hysteretic current for higher ranges will cause an increase in the higher harmonics, but the rapid diminution in the permeability on approaching saturation will cause a much greater increase in these harmonics, so that even at higher ranges the distorting influence of hysteresis is comparatively slight.

As a final conclusion, then, we may say that Prof. Rowland's hypothesis that the higher harmonics in the transformer for sinoidal E. M. F. are due, not to hysteresis, but to variation in permeability, and that the effect of hysteresis may be represented by a constant resistance, is approximately correct, for reasonably good iron, is very nearly correct for the moderate ranges used in practice, and may, under certain conditions, be absolutely correct.

A study of hysteretic characteristics would no doubt shed some light on the phenomena of magnetism, but it is beyond the scope of this paper.

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## Discussion.

Mr. A. E. Kennelly:—It seems to me that this paper is capable of having its principal result summed up in comparatively few words. If the hysteresis cyclic diagram or loop in the case of iron enclosed no area, but consisted of a pair of lines immediately side by side, there would be no energy required to magnetize the iron, and the permeability of the iron would simply change as the magnetism altered. There would then be harmonics in the current wave curves, but there would be no dissipation of energy in the iron. The paper says that if you take the energy which is due both to hysteresis and to eddies, and suppose that the energy is expended just as in a resistance, that is by a current in phase with the electromotive force—if you could imagine that current to exist—and then subtract that current from the current actually observed, you will find a nearly symmetrical curve at right angles to the electromotive force. That is a question which does not conflict, it seems to me, with the existing theory of hysteresis in transformers.

Dr. Nichols:—I regret that Prof. Ryan is not present to-day, as I am sure he would be very much interested in this paper. I hope we shall have the privilege of hearing from Mr. Steinmetz, who has contributed so much to our knowledge of this subject.

MR. STEINMETZ:—While I would like to add a few remarks, I must first express my pleasure to have listened again to a paper, which will not be superseded and worthless in a year or two, as other papers read here have become.

The paper first discusses the question, whether hysteresis or permeability is the cause of the distortion of wave shape in transformers. I do not think there is really any difference in the explanation of the phenomenon by hysteresis or by varying permeability. Hysteresis, according to the derivation of the word, means the discrepancy between magnetizing force and magnetism, consisting in a lag of the latter behind the former. Thus hysteresis presupposes or rather represents an unsymmetrically varying permeability, and thus a distortion of the wave shape due to hysteresis is nothing but a particular case of the distortion due to varying permeability. In my third paper on the "Law of Hysteresis," I have shown a number of instances of distortion of the current wave, independent of hysteresis, by varying permeability, or rather permeance, in the case of a magnetic circuit of periodically varying reluctance. Further on, the paper attempts to separate the effect of varying permeability into two components, one, the energy component, representing the molecular magnetic friction; the other, the wattless magnetizing component.

In my third paper on "Hysteresis," I have discussed and carried through this separation analytically, by the introduction of the "effective" or hysteretic resistance. I have, however, operated all the way through with the equivalent sine wave irrespective of the real wave shape. In this respect this paper offers an essential step in advance, by dissolving the real or observed current wave into two components, the energy and the wattless component, and showing that the energy component is practically a sine wave, and that the distortion observed in the total wave is due essentially to the magnetizing component. This is eminently interesting, since it proves the permissibility of representing the loss by molecular magnetic friction by a constant quantity, an effective resistance or effective conductance.

One assumption, however, is made in the derivation of these results, which may be taken exception to. In the hysteretic cycle, the two values of K. M. F. corresponding to the same magnetization are averaged, and this average curve used as the magnetization curve in plotting the magnetizing current, while the difference between this curve and the hysteretic loop is used for plotting the hysteretic energy current. This difference, or the hysteretic characteristic, is found to be approximately the quadrant of an ellipsis.

In Fig. 1 is shown the hysteretic loop corresponding to the curves shown as Fig. 6 in my paper on "Hysteresis," part 3, plotted in percentages of the maximum value, F—M denotes the hysteretic loop, G the magnetizing curve or curve of average

M. M. F. as used by Mr. Huguet, and H denotes the hysteretic characteristic.

There is no inherent reason why the average M. M. F. should be used as magnetizing curve, and not, for instance, the magnetization curve derived by plotting the average of the two values of magnetism corresponding to the same M. M. F., as shown by V in Fig. 1, or directly the observed magnetization curve A, as derived by electro-dynamometer tests or ballistic galvanometer and the method or reversals. Using the curve A for deriving the wave of magnetizing current, we would get the curve A in Fig. 2, which passes steeply through the zero point, and in general shows a distortion just opposite to that of the curve C, used by the writer; and thus the curve A would not make the energy component of current H a sine wave, as shown in Fig. 2.

In favor of the assumption made by the writer is, however, a feature, to which I drew attention some time ago, namely, that the initial inward bend of the observed magnetic hysteretic A in Fig. 1 is probably an effect of molecular magnetic friction, while the true magnetic characteristic of the material in the absence of hysteresis is a curve similar in shape to the curve C, and very closely resembles the arc of a hyperbola, as shown by Mr. Kennelly in his paper on "Reluctance." When observed under conditions where hysteresis is absent, that is, where the energy consumed by molecular magnetic friction is supplied by some outside source, as for instance an alternating current passing lengthways through the magnetic circuit, the hysteretic loop collapses, and the rising and decreasing magnetic characteristics coincide in the hyperbola. If no energy is supplied from the outside, the magnetization curve at low density cannot follow this curve, since the loss of energy by molecular magnetic friction when rising on this curve would be in excess to the total amount of energy supplied to the magnetic circuit.

That is:

$$\eta B_0^{1.6} > \int_{-B_0}^{+B_0} B\,d\,F,$$

where $B_0$ = maximum magnetization,
$B$ = magnetization,
$F$ = M. M. F.,
$\eta$ = coefficient of hysteresis.

It would be of interest to investigate this field experimentally, and it could be done probably by winding the core of a magnetic circuit with very fine insulated iron wire, send an alternating current of high frequency through this wire, and then determine the magnetizing current curve of a coil surrounding the magnetic circuit, by the instantaneous contact method, and an alternating current low in frequency compared with the alternating length current in the iron of the magnetic circuit.

If, as it appears from this paper, the hysteretic characteristic is the arc of an ellipsis, while the true magnetization curve is the arc of a hyperbola, the hysteretic loop could be represented analytically by the product of two quartic curves, a result which is very interesting.

As you see, this paper offers quite a number of points of theoretical and practical interest and an ample field for further investigation, and I am therefore very glad that it has been secured for the INSTITUTE.

MR. HUGUET:—In regard to the similarity of hysteresis and variation of permeability, I cannot quite agree with Mr. Steinmetz. If we consider the value of $\mu$ in a loop as being dependent on the ratio of the flux to the magnetizing current, then $\mu$ would be zero at $a$ and $a'$, infinite at $b$, and negative from $b$ to $a'$,

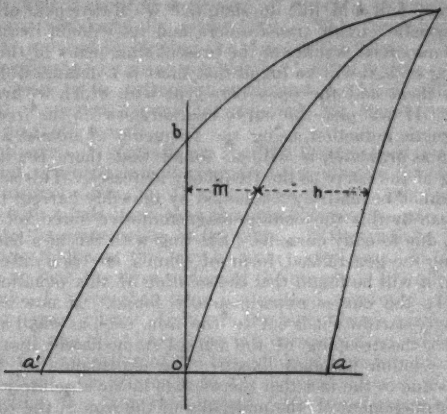


FIG. 8.

all of which we know to be impossible. As a matter of fact, $\mu$ should be derived from a curve passing through zero and everywhere intermediate between the rising and descending limbs. Such a curve answers all requirements. This assumption is, in fact, always made, for curves of $\mu$ are always single-valued, and hysteresis is either neglected or actually eliminated by vibration or otherwise. If hysteresis is present, as in a loop, the magnetizing current at any flux is then not simply the current required by the value of $\mu$ at that flux, but it is necessary to add the hysteretic current. This hysteretic current is in absolute value a function of the flux, the relationship being expressed by the hysteretic characteristic, and its sign is determined by the direction of change of the flux, positive for the rising limb, and negative for the descending. [See Fig. 8.]

MR. C. T. RITTENHOUSE:—I think that Prof. Ewing, in a paper presented before the International Electrical Congress, held at Chicago in 1893, made the statement that a distinction must be drawn between the permeable and hysteretic qualities of iron, since specimens showing good permeable qualities need not necessarily possess good hysteretic qualities. Mr. Huguet has made Prof. Rowland the single exception to the theory that upper harmonics are due to hysteresis. In 1894, at the Philadelphia meeting of the INSTITUTE, if I am not mistaken, it was this very point which was the subject of animated discussion between Dr. Pupin and Mr. Steinmetz, and although Dr. Pupin did not explain at that time the real cause for upper harmonics, he laid particular stress upon the fact that his experiments showed that upper harmonics could not be due to hysteresis. In reference to this paper, I would like to state that we always hear of closed ferro-magnetic circuit transformers, and yet I doubt if there exists in commercial practice at the present time many of this type. In testing such, it will be found that there is a distinct difference between them and the open core type with which we are more familiar. If we plot the curve relation between the frequency and magnetic induction, using the frequency as abscissa and the induction as ordinates, it will be found that there is a decided drooping of the curve as the frequency increases. This action, I think, cannot be entirely explained by the eddy current theory, if we mean by this the counter-magnetomotive force set up in the iron, due to eddy currents. Starting with this as a basis and expressing the generalized form of Ohm's law as a differential equation, it will be found that the solution of this equation does not satisfy the curves experimentally found. If now even an exceedingly narrow slit is cut in the iron, even as small as .001 of an inch, the drooping of the curves immediately disappears and the relation becomes linear. The explanation of this is doubtless due to the fact that there exists in the absolutely closed core an arrangement of the molecules of the iron in the form of closed chains, and owing to the reluctance with which these chains are broken up, a considerable demagnetizing force is required before a change is effected when suddenly the chain is ruptured and oscillations appear to be set up, which produce distortions in the current wave. If this hypothesis be true, and experiment seems to warrant its assumption, it would indicate that not only hysteresis is to be excluded as a cause of harmonics, but under certain conditions, permeability also.

MR. C. A. ADAMS, JR.:—There is one transformer which was manufactured a few years ago by the Brush Electric Company, of Cleveland, of which the magnetic circuit is completely closed. The core punchings were in disk form, similar to those for armature cores, and the winding was done entirely by hand.

MR. RIES:—I would state that a closed magnetic circuit was used in the Ries regulating socket—not as converter particularly,

but as a reaction coil, although I have also successfully used the same construction for converters. The coil was wound by hand, and in order to facilitate the winding, the coil was in the form of a cable containing a number of separate wires.

MR. RITTENHOUSE:—Experiment shows that the magnetizing current for the closed core type is much reduced as compared with the type having a butt joint. This naturally follows from the fact that the reciprocal of the reluctance is directly proportional to the power factor. It would seem, therefore, that the small closed ferro-magnetic circuit transformer, although more expensive to construct, might possess qualities deserving some commercial consideration.

MR. C. A. ADAMS, JR.:—From experiments on butt joint transformers, I have found that the magneto-motive force required for the joints is about five per cent. of the total, in a transformer of fair size with carefully made joints. This percentage is considerably reduced by lapping the plates at the joints, so that the gain in efficiency by using completely closed magnetic circuits is readily seen to be extremely small and not at all sufficient to warrant the extra expense of winding the transformer with closed magnetic circuit.

MR. SCOTT:—It seems to me that the transformers made with lap joint magnetic circuit approach very close to the absolutely closed magnetic circuit. If two plates of iron be brought together with a butt joint, then the area between the two is equivalent to the cross-section of the plate. If the plate be 100th of an inch in thickness, this may be a very small area. If the plates lap for an inch, the cross-section of the air-gap is a hundred times as great. I agree that there is a marked theoretical difference between open circuit transformers and closed circuit transformer. I also think that there is a corresponding difference in the practical operation of the two kinds of transformers.

MR. RIES:—In reference to the lapped joints of closed circuits, while it is true that lapped joint transformers are much better in general than the open coil or butted joints, yet on the other hand, from a mechanical point of view, the construction becomes more difficult and the space occupied after assembling the parts is very much larger than in the case of closed plates or rings which are cut out of the solid sheet metal and placed closely together. In that way you get a better and more efficient type for a given size and weight. I have come to the conclusion from numerous experiments that I have conducted, that that type, where it can be used, is by far the best.

MR. RITTENHOUSE:—The reason I brought up the question of closed and open ferro-magnetic circuits was not with any intention of advocating the use of the former type of transformer, but for the purpose of pointing out that Mr. Huguet had not conclusively shown that the cause of upper harmonics was in all cases to be attributed to variable permeability.

[Recess until 2 P. M.]

## NOTICE.

Members who have not yet received bound Vol. XII for 1895, should notify the Secretary to that effect. All are entitled to copies who have paid their dues up to May 1st, 1896—not May 1st, 1897 as many seem to have understood.

RALPH W. POPE, Secretary.

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## Applications for Membership.

Applications have been received from the following candidates and will be acted upon by Council at its next meeting :

| | |
|---|---|
| Charles G. White, Lake Linden, Mich. | Charles W. Richards. Boston, Mass. |
| Julio Pinkas, Sucre, Bolivia. | F. J. Newbury, Trenton, N. J. |
| H. M. Brinckerhoff, Chicago, Ill. | H. G. Meadows, Buffalo, N. Y. |

Should a member object to the election of any of the above candidates, he should notify the Secretary to that effect prior to September 23d.

RALPH W. POPE,
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RALPH W. POPE, Secretary.


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